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CONCENTRATION AND SIZE DISTRIBUTION OF AIRBORNE DUST PARTICLES IN A HORIZONTAL DUCT FOLLOWING A VENTURI [Benchuri koho no suiheikannai ni okeru funjin no bunpu to ryudo bunpu]

by

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Measurements were made of the particulate concentration and size distribution in an air-talc suspension across a horizontal circular duct downstream of a Venturi. A cascade impactor was used for determination of concentrations and size distribution of dust in small samples of the suspension extracted from the dust.

The experimental results indicated that the particles, like the air velocity, remained uniformly distributed, except for sampling positions immediately next to the wall of the duct, and the Venturi was efficient, both for obtaining uniform flow, and also ensuring that a dust sample extracted at a single point near the center of the duct will be representative of the whole suspension. Thus, the Venturi was suggested to facilitate single-point sampling, from the point of view of ease of operation.

Concerning size distribution, some interesting performance data were also presented, which confirmed the possibility of using the cascade impactor as an aerosol-sizing device, capable of giving direct size-analysis figures of dry dust.

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I. Introduction

In order to determine the efficiency of a dust collector, it is necessary to measure the concentration of airborne dust particles at its inlet and outlet. JIS S 8808, which specifies the methods for measuring soot and dust in exhaust gas ducts, also applies to the measurement of concentration of general industrial dust particles. However, it requires a large number of sampling points in proportion to the area of exhaust dust section in order to obtain an average concentration. Equal-speed suction must be applied at each sampling point, an essentially complicated operation, thus making the measurement substantially more complicated.

Hyomi et al. [3] reported as follows: The concentration distribution of dust particles in a horizontal straight-exhaust duct was determined by the dust-tube and filter-paper methods. Using the correlation formula of the thus-obtained horizontal concentration distribution, the concentration at sampling points other than the center can be calculated from the concentration at the center. As a method of determining the average gas flow velocity and dust concentration from measurements at a single sampling point in the center of the duct, Stairmand et al. [4] also proposed placing a disturbance plate at the center of the duct to disturb the gas flow and obtain uniform velocity and concentration distribution.

Here we will show that an almost uniform gas flow distribution and dust particle size distribution are obtained in the lower stream, near the Venturi, placed inside the horizontal duct. This data is relevant to the simplification of methods for measuring dust particles in a

duct at any one time; the results of size-distribution measurements of dust particles by a cascade impactor will be discussed.

2. Apparatus and Method

2.1. Apparatus

An overall schematic of the apparatus is shown in Fig. 1. A horizontal circular duct with an inside diameter of 125 mm, made of transparent acrylic resin, was used in the measurement. The blower pressurizes the air and sends it to the Venturi, which is connected to the upper part of the stream through the flow-measuring quadrant nozzle. The airstream absorbs dust particles supplied in a fixed quantity through a feeder. These particles are eliminated from the system after passing through the measuring part of the horizontal duct and the cyclone. Fig. 2. gives the details of the Venturi.

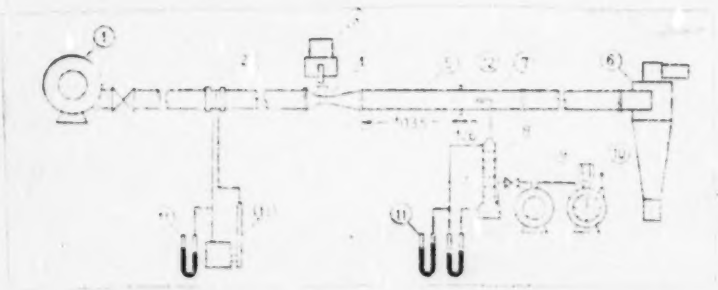

Fig. 1. Overall schematic of apparatus

Key:
1. Blower
2. Quadrant nozzle
3. Feeder
4. Venturi
5. Measurement section
6. Cyclone
7. Probe
8. Cascade impactor
9. Vacuum pump
10. Wet gas meter
11. Pressure gauge
12. Static pressure tap
13. Goettingen fine pressure gauge

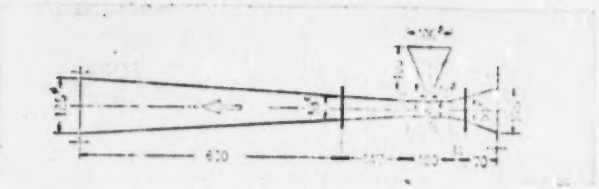

Fig. 2. Detail of Venturi

The sample particles are talc, with a density of 2.74 g/cm^3, whose size distribution corresponds to the four kinds of talc listed in JIS Z 8901.

2.2. Determination of Dust Concentration

The dust concentration in the duct was calculated from the quantity of supplied dust particles and transported air. However, the amount of air that is measured by the quadrant nozzle does not include the amount of air drawn in by the Venturi together with the dust particles. The quantity of transported air cannot be measured directly. Therefore, an indirect method, using the pressure loss at the attached cyclone, was employed in this measurement. The average air velocity, Um, at the cyclone inlet was measured by the quadrant nozzle when the dust-particle passage at the Venturi was closed. Then, the relation of the average air velocity and the measured value of the pressure loss, Δp, as shown in Fig. 3, gave the following formula, applicable to cyclones in general:

$$\Delta p = F \frac{\rho Um^2}{2g_c} \qquad (1)$$

where F is the pressure loss coefficient, ρ is the air density and g_c is the gravitational conversion factor. A resultant F of 8.4

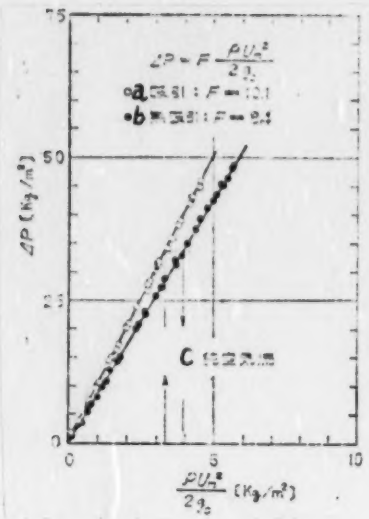

Fig. 3. Plot of Δp vs. $\rho Um^2/2g_c$

Key: a. Suction
b. "No suction"
c. Pure air stream

was obtained. On the other hand, when the particle-supply passage was opened and air was drawn in by the Venturi, a similar relation was established between Δp and the apparent wind velocity at the inlet, calculated by neglecting the suction as shown simultaneously in Fig. 3; a resultant F of 10.1 was obtained. From Fig. 3, it is obvious that the differences in the values of the abscissa in the cases of suction and "no suction" is based on the quantity of air drawn in. First, the apparent wind velocity at the inlet when suction was disregarded was measured by the quadrant nozzle; then, from Fig. 3, the "no suction" wind velocity at the inlet which gives the same Δp was determined.

Hence, the average wind velocity at the measuring point in the duct and the quantity of transported air were obtained.

As is apparent from the figures, the flow ratio of the air sucked in, relative to that of the mainstream, is $1 - \sqrt{8.4/10.1} = 0.088$, regardless of the velocity of the mainstream.

2.3. Measurement of Flow Velocity and Particle Concentration Distribution

The collection probe employed during suction of part of the air-stream containing dust particles is shown in Fig. 4. Probe I was built

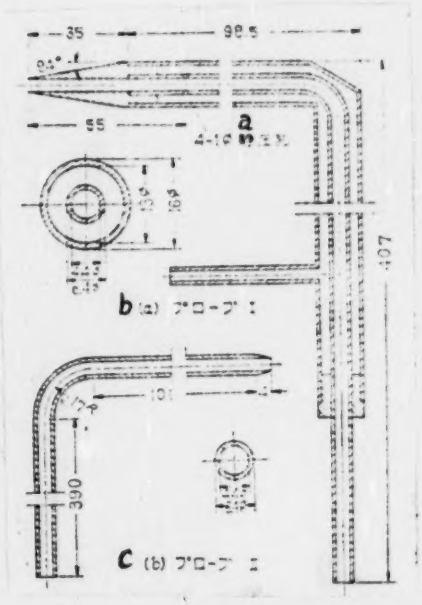

Fig. 4. Details of sampling probe

Key: a. Static pressure hole
b. Probe I
c. Probe II

in order to facilitate equal-speed suction, where the suction speed was matched with the mainstream velocity by equalizing the static pressure in the inner tube and the duct wall. However, the actual suction speed was not in agreement with this, for example, 6 m/sec as opposed to the mainstream velocity of about 9 m/sec. It is conceivable that this is because the static pressure hole of the inner tube of the probe was placed at a substantial distance from the inlet. Therefore, due to friction and contraction losses at the inlet, the measured pressure appeared less than the static pressure immediately before the inlet. When suction was equalized for both inside and outside static pressure, the suction speed would be less than the mainstream speed. This error cannot be avoided in a balance-type probe, which usually has some mechanism to adjust the amount of gas sucked in by equalizing the static pressure at the inner and the outer walls near the entrance [1]. Therefore, when these types of probes are used for measurement, it is necessary to correct the suction speed using a correction curve determined in advance by comparing the mainstream speed and the suction speed. However, this type of correction was not conducted here; instead, the speed distribution of the mainstream in the duct was measured in advance, as in the case of Probe II. Subsequently, suction speed was equalized by matching it with the flow speed inside the probe.

An L-type Pitot tube was employed for measurement of the stream velocity distribution inside the duct in the case of the pure airstream. However, in the case of the dust-containing airstream, there is the possibility of clogging the pressure hole of the Pitot tube. Therefore,

the aforementioned probe was employed as a total pressure tube and was corrected by the Pitot tube. The flow velocity was calculated without consideration of the influence of the dynamic pressure based on the momentum exchange of dust particles, since the concentration of the dust particles within the range of the experiment was low.[1]

The cascade impactor used in the separation and collection of dust in the airstream drawn in and collected through the probe was a combination separator/collector consisting of a six-step impact nozzle and collection plates and a millipore filter connected in series, and was available to the public.[2]

When there is a rescattering of particles on the collection plates, the fine distribution on the screen appears greater than the true distribution. Iiya et al. performed a detailed study on the separation structure of cascade impactors [5, 6] and on particle size measurement method using impactors [3, 7]. They reported that rescattering becomes apparent when the particle quantities reach 250, 140, 100, 50, 15 and 10 mg at steps no. 1 to 6, respectively [3]. They also noted that the quantity of particles on the first to third collection plates should be

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[1] The range of this measurement is 2.4 - 19 g/m^3 as later indicated. The dust concentration at the inlet of an industrial dust collector has a wide range of 0.1 - 100 g/Nm^3, except in the case of air transport in which the concentration is 1000 ~ 2500 g/m^3. However, the usual range of concentration is 20 - 30 g/Nm^3.

[2] Constructed by Seisan Kaihatsu Kagaku Kenkyujo (Production Development Science Laboratory), Japan.

less than 50 mg. However, in our experiment, the collection quantity was the greatest at the first step, between 50 and 70 mg, but never exceeded 80 mg. Dust-particle deposits were found on the inside wall of the nozzle as well as on the collection plates. This was especially noticeable at the first step. It was uncertain where the deposit belonged and it was not included in the collected dust at the time of size measurement.

Table I. Sampling positions

Sampling point	y/D	Sampling point	y/D	Sampling point	y/D
1	0.975	5	0.662	10	0.267
1'	0.937	6	0.583	11	0.188
2	0.900	7	0.500	12	0.108
3	0.820	8	0.425	13	0.063
4	0.741	9	0.346	13'	0.055

y: Vertical distance from the bottom of the duct
D: Diameter of the duct

All measurements were performed at a point 1160 mm behind the entrance of the horizontal duct (approximately nine times the diameter of the duct), and the dust airstream was collected at each measurement point shown in Table I.

No special consideration was given to charged electricity on the dust particles.

3. Result and Discussion

3.1. Flow Velocity Distribution

Fig. 5 shows the flow velocity distribution inside the duct u in the case of a pure airstream. As is obvious from the figure, the flow velocity distribution is almost flat and had not yet developed into a

perfect turbulent flow velocity distribution at the measurement position. Although the velocity distribution of the dust-containing airstream is not shown in any figure, there was no noticeable difference between it and the pure airstream. In Fig. 5, the tendency of the lower stream velocity to be a little greater than that of the upper stream is noted. This is thought to be due to suction of the airstream from the upper part of the throat of the Venturi.

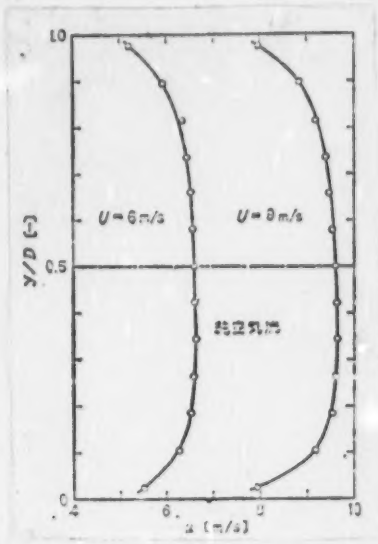

Fig. 5. Velocity distribution across the duct

Key: a. Pure airstream

3.2. Concentration Distribution

Figs. 6 and 7 show results of measurement of the concentration distribution by Probes I and II, respectively. The dust concentration obtained from the quantity of the dust collected on the collection plates of the cascade impactor amounted to only about half the supplied dust

concentration C_f. Therefore, the concentration was calculated again by adding the aforementioned dust particles deposited on the inside wall of the impactor. From the figure, it is obvious that dust particle concentration c obtained at each sampling position was about 80% of C_f and showed an almost flat distribution. The quantity of dust deposits on the tube walls of the probes was not measured and remained unknown, together with the dust deposits inside the horizontal duct, and this is probably the cause of the error.

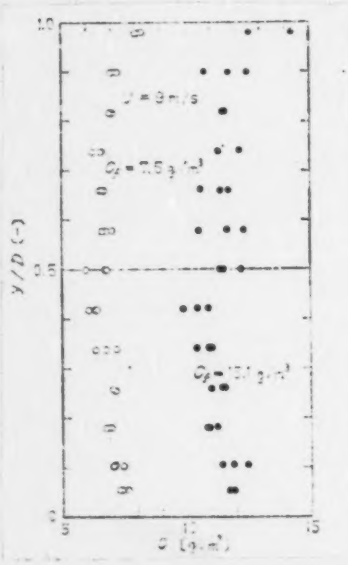

Fig. 6. Concentration distribution across the duct (measured with Probe I).

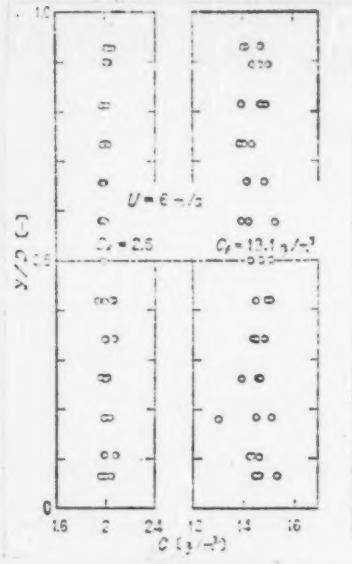

Fig. 7. Concentration distribution across the duct (measured with Probe II).

From the fact that a flat concentration distribution was obtained at a cross section of the duct after the Venturi, we can expect a simplification of measurement operations by sampling the dust stream at a single sampling point near the center of a cross section similar to the Stairmand disturbance plate.

Moreover, the concentration tends to be slightly higher close to the upper and lower duct walls than around the center (Fig. 7)[1]. This tendency agrees with the reports of Yu et al. [8] and Hyomi et al [2]. However, it is not as obvious as in their experiments. The following is considered to be the reason for a higher concentration near the duct wall than around the center: It is thought that there is a stronger turbulence around the center of the duct than around the wall, and it carries the dust particles from the central part in the direction of the wall. However, it was thought that the appearance of little increase in concentration at the sampling positions, except locations near the wall, was due to lack of development of the boundary layers and laminar boundary layers near the duct wall, this being obvious from the aforementioned results of flow velocity distribution measurements.

Although the concentration is generally higher near the bottom of a duct at a slow velocity of less than 15 m/sec, due to the influence of sedimentation caused by the gravitational force, this influence was

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[1] Probe I is more restricted in measurement immediately near the duct wall due to structural differences. This tendency is not clear in Fig. 6.

not clearly noted in our experiment in spite of the slow flow velocity of U = 6 and 9 m/sec.

3.3. Size Distribution

Figs. 8 and 9 show the results of size distribution. As is apparent from Fig. 8 (a) and (b), the size of the particles measured by Probe I is distributed almost uniformly as in the case of concentration distribution. However, the measurement results of Probe II shown in Fig. 9 (a) and (b) show a rather rougher screen distribution at sampling points near the duct wall than at other locations. This is interesting because it agrees with the reason why an increase of concentration occurred near the duct wall and cohesion of dust occurred more easily than at other sampling positions. The influence of this cohesion occurs more frequently at lower flow velocity and higher concentration, and the apparent size becomes rougher, as shown in Fig. 8 (a) and (b). It makes it easier to understand the advantages of a cascade impactor, which can directly measure the size distribution of the dust particles suspended in the airstream. The influence of the concentration on cohesion was hardly noticeable in the measurement results of Probe II shown in Fig. 9. We must leave discussion regarding this for the future.

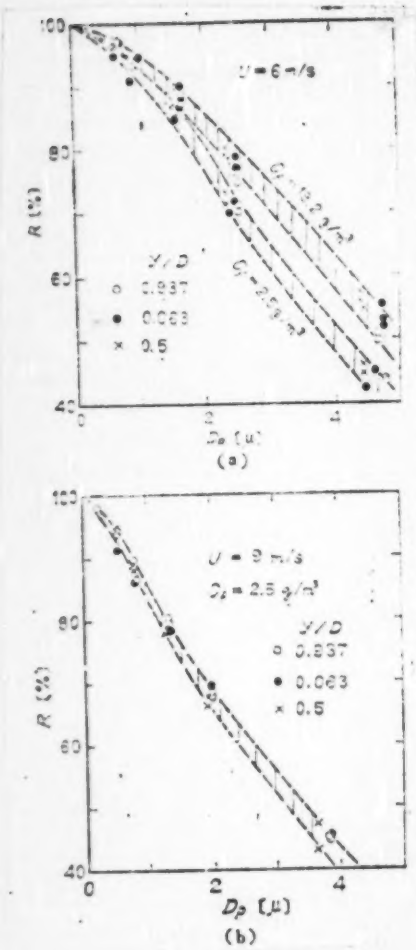

Fig. 8. Size distribution across the duct (measured with Probe I).

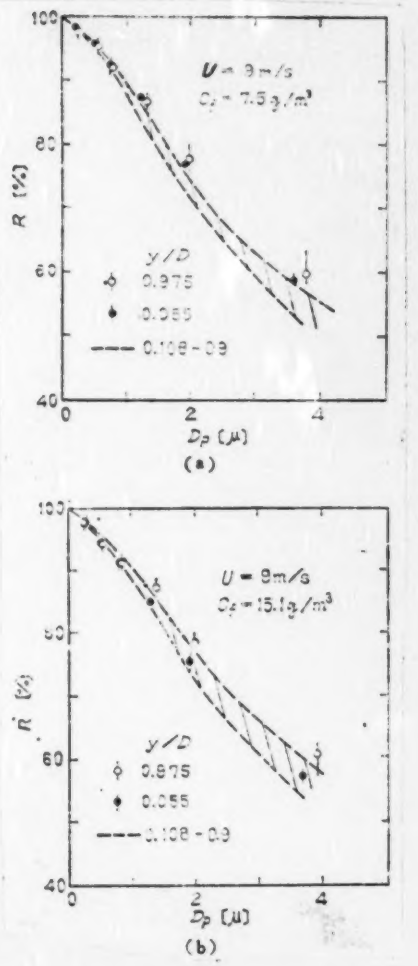

Fig. 9. Size distribution across the duct (measured with Probe II).

4. Conclusion

The vertical velocity and concentration distributions of dust suspended in an airstream flowing at a relatively low flow velocity was measured downstream from a Venturi inside a horizontal circular duct. The results showed that these distributions were almost flat, except near the duct wall. They also pointed out the possibility of simplification of the multi-sampling position method specified by JIS.

The influence of dust cohesion was almost always clearly related to the flow velocity and the concentration in the results of size measurement by the cascade impactor. Hence, we were convinced that a cascade impactor was quite useful in direct measurement of the dust-particle size simultaneously with concentration measurements. The merits of a cascade impactor as a dry measurement instrument are expected to encourage future success in the application and popularity of this instrument.

When a Venturi is used at the connection of a large-diameter duct, the straight part becomes long, and the whole apparatus becomes huge. It may restrict the use of the Venturi. A Venturi also has the disadvantage of large pressure loss, as seen in Venturi scrubbers. However, the Venturi can be designed so as to minimize the pressure loss to less than that of squeeze-type disturbance plates. Also, the clogging caused by dust deposits in a Venturi seems to be much less than in the case of a disturbance plate.

Notation

C_f: Supplied dust concentration.
c: Collected dust concentration.
R: Accumulated screen distribution
U: Apparent flow velocity in the duct.
D: Diameter of the duct.
D_p: Diameter of dust particle.
F_p: Pressure loss coefficient.
g_c: Gravitational conversion factor.
Δp: Pressure loss.
ρ: Gas density.
Um: Apparent flow velocity at the entrance of the cyclone.
u: Airstream velocity.
y: Vertical distance from the duct bottom.

Cf: (g/m^3)
c: (g/m^3)
D: (mm)
D_p: (μ)
F_p: (-)
u: (m/s)
g_c: $(kg \cdot m/kg \cdot sec^2)$
Δp: (kg/m^2)
R: (%)
U: (m/s)
Um: (m/s)
y: (mm)
ρ: (kg/m^3)

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